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REPORT 79–29

GEOLOGICAL DISPOSAL OF HIGH–LEVEL RADIOACTIVE WASTES

D.F. COATES, G. LAROCQUE AND L. GELLER

MINERALS RESEARCH PROGRAM
MINING RESEARCH LABORATORIES

Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

NOVEMBER 1979

Available in Canada through

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Hull, Quebec, Canada K1A 0S9

CANMET
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555 Booth St.,
Ottawa, Canada K1A 0G1

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Catalogue No. M38–13/79-29
ISBN 0-660-10523-3

Canada: $1.50
Other countries: $1.80

Price subject to change without notice.

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N^o de catalogue M38–13/79-29
ISBN 0-660-10523-3

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by

D.F. Coates*, G. Larocque** and L. Geller***

ABSTRACT

The importance of nuclear powered electricity generation in helping to solve Canada's future energy requirements is well documented. It is also well known that whereas nuclear reactors are technically feasible, they also involve serious human and environmental problems which remain to be solved. One problem is safe disposal of the various types of radioactive wastes. Mining waste and mill tailings containing toxic radium are produced in large quantities. It is believed about 80 million tonnes have already accumulated at Elliot Lake, Ontario, alone and that this may increase by the year 2000 to several hundred million tonnes. These tailings are large in bulk but relatively low in radioactivity.

Wastes from nuclear generating stations, on the contrary, are highly radioactive but relatively small in volume. This report provides a brief overview of how electricity is generated by means of nuclear power, and gives reasons which render safe disposal of high-level nuclear wastes a particularly difficult and multifaceted problem. It is suggested that under Canadian conditions deep underground burial of these wastes in mined-out facilities within igneous rocks is the most acceptable solution.

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ELIMINATION GEOLOGIQUE DES DECHETS A RADIOACTIVITE PERMANENTE

par

D.F. Coates*, G. Larocque** et L. Geller***

RESUME

L'importance de la production d'électricité dans les centrales à énergie nucléaire pour répondre aux besoins futurs des Canadiens a fait l'objet de plusieurs études. On reconnaît aussi que malgré la possibilité technique des réacteurs nucléaires, ils occasionnent de sérieux problèmes tant du point de vue humaine, que de l'environnement qui doivent être résolus. Un de ces problèmes est l'élimination sans danger des différents types de déchets nucléaires. Les déchets des mines et les stériles des usines contiennent du radium toxique et sont produits en grande quantité. On estimée à environ 80 millions de tonnes les déchets déjà accumulés à Elliot Lake (Ontario) et cette quantité pourrait atteindre plusieurs centaines de millions de tonnes vers l'année 2000. Ces stériles, quoique abondants, ont un niveau de radioactivité relativement bas.

Les déchets provenant de centrales à énergie nucléaire sont au contraire très radioactifs quoique en très petit volume. Ce rapport donne un bref aperçu de la production de l'électricité par l'énergie nucléaire et explique les raisons pourquoi l'élimination sans danger des déchets à radioactivité permanente est un problème si difficile et complexe à surmonter. On conclut que compte tenu des conditions du Canada, l'enfouissement souterrain de ces déchets dans les endroits exploités à cette fin parmi les roches pyrogènes est la solution la plus acceptable.

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GROWTH OF NUCLEAR POWER GENERATION IN CANADA

The increase in electrical power generated by CANDU type nuclear reactors in Canada within the past 10 to 15 years has been spectacular. From the modest 25 MW(e) generated at Rolphton, Ontario, in 1962, it had grown by 1977 to 4500 MW(e) or about 27% of all electricity generated by Ontario Hydro. Additional stations currently under construction in Ontario will expand the province's nuclear generating capacity to some 13 500 MW(e) by the late 1980's, nearly 50% of Ontario's electricity supply.

Nuclear electric generating stations are under construction or planned primarily for locations in Ontario; however, a few are scheduled for other provinces (Table 1). Although forecasting electric generating capacity even in general terms, let alone in nuclear capacity, is difficult, it seems certain that nuclear power will play an increasingly important role in Canada's future energy supply. It has been suggested that by the year 2075, Canada will have installed nuclear electric generating capacity ranging between 13×10^4 and 220×10^4 MW(e). This will represent a sizable percentage of Canada's entire generating capacity.

As a result of this increased growth, a corresponding rise in the volume of highly radioactive waste products and spent fuel will also occur. Spent fuel consists of fuel bundles that have been used and then withdrawn from the reactors; the remaining wastes are all other radioactive materials

Table 1 - Existing and planned Canadian nuclear power stations (From "The Canadian Nuclear Power Program" by J.S. Foster; AECL-5534; May, 1976)

Station	Operating units	Unit rating MWe(net)	Power system	Start of operation
NPD	1	22	O.H.(1)	1962
Douglas Point	1	208	O.H.	1966
Pickering "A"	4	514	O.H.	1971-73
Gentilly 1	1	250	H.Q.(2)	1971
Bruce "A"	4	745	O.H.	1976-79
Gentilly 2	1	600	H.Q.	1979
Lepreau	1	600	NBEPC(3)	1980
Pickering "B"	4	514	O.H.	1981-83
Bruce "B"	4	750	O.H.	1983-86
Darlington	4	800	O.H.	1986-88
X	1	600	M.H.(4)	1985+

(1) O.H. - Ontario Hydro
(2) H.Q. - Hydro-Quebec
(3) NBEPC - New Brunswick Electric Power Commission
(4) M.H. - Manitoba Hydro

resulting from the normal operation and maintenance of CANDU type generating stations. Both of these main types of products must initially be stored and finally disposed of safely. Storage is the temporary emplacement of radioactive wastes in a safe location for later retrieval; disposal is permanent emplacement.

It is uncertain as yet whether both types of waste will be disposed of in the same facility. However, present policy is to operate the CANDU system on a once-through natural uranium cycle, without reprocessing the spent fuel for plutonium. The irradiated fuel, therefore, contains the great bulk of the radioactive material to be safely disposed of.

NUCLEAR POWER GENERATORS

To generate electricity with steam-turbine driven generators it is necessary to raise steam by heating water. In most conventionally-fueled boilers the heat is produced by coal or oil. In nuclear powered generating stations the heat is produced by the fission process that occurs when a neutron is absorbed by certain heavy elements such as uranium-235 or plutonium-239 (Fig. 1). This process produces neutrons, fission products and heat (Fig. 2).

Radioactive fission

Fission is a process in which uranium-235 or plutonium-239 is split into two approximately equal parts, called fission products, as a result of collisions between uranium or plutonium atoms and neutrons. Some of the fission products, or nuclides, are unstable and decay radioactively. In addition to fission products the reaction also produces more neutrons and releases large amounts of heat energy.

In this report the term fission products is understood to include both the lightweight fragments as well as the actinides. The latter is the group of elements whose atomic number, i.e., the number of protons in their nucleus, varies from 89 for actinium to 103 for lawrencium. Nuclides are species of atoms characterized by the constitution of their nucleus. The positively charged core of an atom is known as the nucleus and is composed of one or more uncharged neutrons. The nucleus contains virtually all the mass and is surrounded by orbiting negatively charged electrons equal in number to that of the protons.

The process whereby certain nuclides undergo spontaneous disintegration in which energy is liberated, generally resulting in the formation of new nuclides as well as in one or more types of radiation, is known as radioactivity.

CANDU nuclear reactors

As indicated in Fig. 1, heat is generated within the nuclear fuel bundle; in CANDU reactors the resulting heat is removed by liquid heavy water flowing around the fuel. The heavy water coolant in turn passes through a boiler in which it transfers its heat to ordinary water, thereby producing the steam necessary for driving the ordinary steam turbines. The cooled heavy water is then pumped through the reactor core again in a closed loop to absorb more heat. The nuclear fuel bundle contains about 20 kg of natural

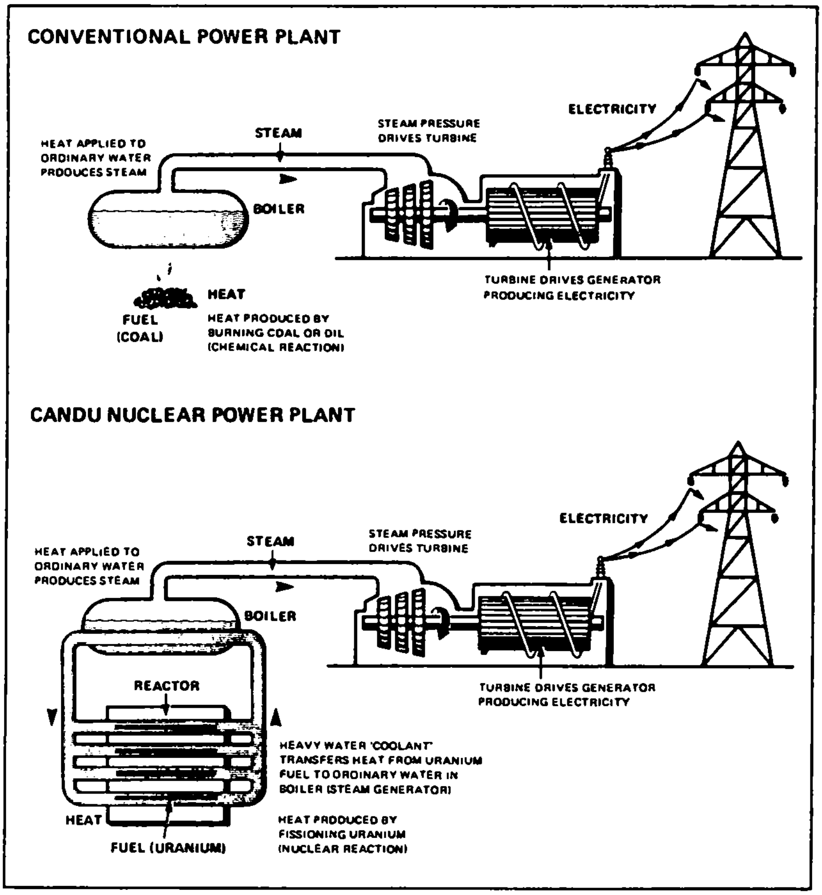

Fig. 1 - Comparison of fossil and nuclear power plants (From "The fundamentals of nuclear power" by G.A. Pon; AECL; 16 p; May 1976.)

uranium. The latter contains two isotopes, namely uranium-235 at about 0.7% by weight and uranium-238. Isotopes are those atoms of an element that have the same number of protons in their nuclei but different numbers of neutrons. All isotopes of an element have identical chemical properties, and therefore cannot be separated chemically.

In the reactor some of the uranium-235 is fissioned, i.e., a heavy atom splits to form two lighter ones or fission product nuclides. A whole spectrum of these is formed, some of which are unstable and thus undergo further radioactive decay. In addition an average of 2.3 neutrons are also released per fission. One of these is absorbed by a fissile atom to keep the nuclear reaction going. The others are absorbed by the materials in the fuel and reactor core, primarily by uranium-238. The latter thus forms uranium-239, which by radioactive decay then becomes plutonium-239 and other heavy elements (actinides). Some of the plutonium-239 is fissile and so, on absorbing a neutron, it too gives off heat, fission products and more neutrons. Nearly 50% of the energy produced during the lifetime of a fuel charge in a CANDU reactor is produced by plutonium fission.

As fission progresses, the concentration of fission products in the fuel bundle builds up. Moreover, other nuclides, e.g., plutonium-239, reach an equilibrium stage at which their rate of formation approaches their rate of decay. At this stage the fuel is considered spent and must be replaced, although only slightly more than 1% of the original natural uranium has as yet been changed and the discharged fuel is still highly radioactive. In other words the fuel still contains much fissile material - about 0.8% fission products and 0.4% plutonium - but these fission products are absorbing too many neutrons. There is also a build-up of isotopes of heavy elements.

HIGH-LEVEL WASTES

Characteristics of spent fuel

As mentioned, the irradiated spent fuel bundles contain a build-up of isotopes of heavy elements that continue to undergo radioactive decay. The latter takes place with emission of radiation and the development of heat. Some of the more important fission products contained in the irradiated fuel are listed in Table 2, together with their half-lives and type of radiation emitted during decay. Half-life is the time span during which half the atoms of a given element disintegrate. It varies from seconds to thousands of millions of years. The variety of elements that must be prevented from polluting the biosphere, and the large variation in the time spans over which this must be done, illustrates the magnitude of the problem in safely storing radioactive wastes.

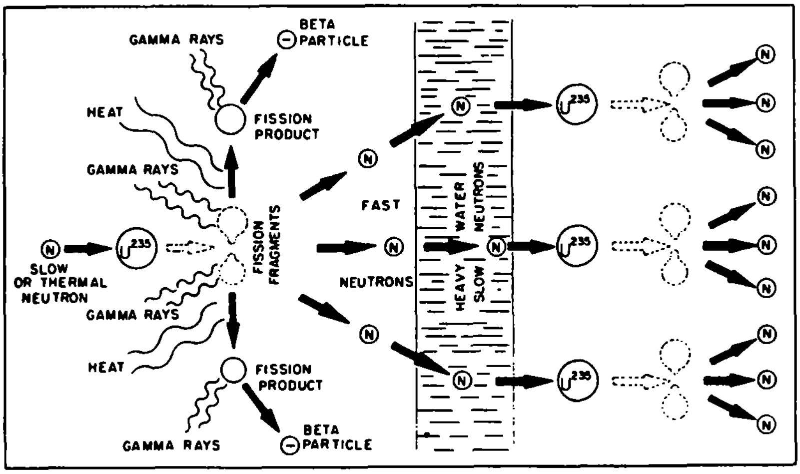

Fig. 2 - Principal reaction in the CANDU system: Bombardment of uranium-235 by slow neutrons causes fission, releasing energy, fast neutrons and fission products. Plutonium-235 is fissionable in a similar manner. (From "Nuclear energy in Canada: Potential and problems" by Th.L. Perry, Jr. in <u>Nature Canada</u>; 3:2; April/June 1974.)

Table 2 - Activities of some fission products in irradiated fuel which are important in waste management, based on Pickering fuel irradiated to 7.5 MWd/kg U (From "Management of radioactive fuel wastes: The Canadian disposal program" by J. Boulton, (ed); AECL-6314; Oct. 1974.)

Radionuclide	Principal radiation	Half-life (years)	Activity (curies/kg U) at discharge	Activity (curies/kg U) after 10 years
Lightweight fission products				
Strontium-90	β	29	17.5	12.9
Iodine-129	β,γ	1.6×10^7	7×10^{-6}	7.9×10^{-6}
Cesium-137	β,γ	30.2	25.3	20.2
Actinides				
Plutonium-239	α,γ	2.4×10^4	0.15	0.15
Plutonium-241	β,γ	14.7	22.9	14.2

Most of the radioactivity of the irradiated fuel during the first few hundred years is due to the lightweight fission products emitting beta and gamma radiation. The most highly radioactive have relatively short half-lives, whereas the extremely long lived have low radioactivity. Consequently, after about 700 years, which is equivalent to about 24 half-lives of the two nuclides, namely strontium-90 and cesium-137, which provide about 99% of the curie content of this group of fission products, the activity is reduced by a factor of about 10 million. Afterwards, the dominant source of radioactivity is the group of heavy elements referred to in Table 2 as actinides whose predominant radiation is the alpha particle. Many of the isotopes of these elements have extremely long half-lives. Thus, about 400 000 years are required for the actinides to achieve the same 10 millionfold reduction obtained with the lightweight fission products in 700 years. More specifically, strontium-90 and cesium-137 have half-lives of 29 and 30 years respectively whereas that of plutonium-239 has 24 000 years. Every 10 half-lives of a nuclide correspond to a 2^{10}, or roughly a thousandfold reduction in radioactivity. Consequently this reduction is achieved in about 300 years with strontium-90 and cesium-137, but only in 240 000 years with plutonium-239. With the exception of iodine-129 it is the actinides that pose the long-term radioactive problems in spent fuel disposal.

The radiation given off by the spent fuel is a form of energy that is converted into heat on absorption. Consequently, the heat, produced by the radioactive decay also decreases rapidly with time. Figure 3 shows this process for: (a) untreated spent fuel bundles, (b) spent fuel from which the plutonium has been removed, and (c) spent fuel from which both the plutonium and the uranium have been removed. As shown there is no difference between these three cases during the first ten years of storage.

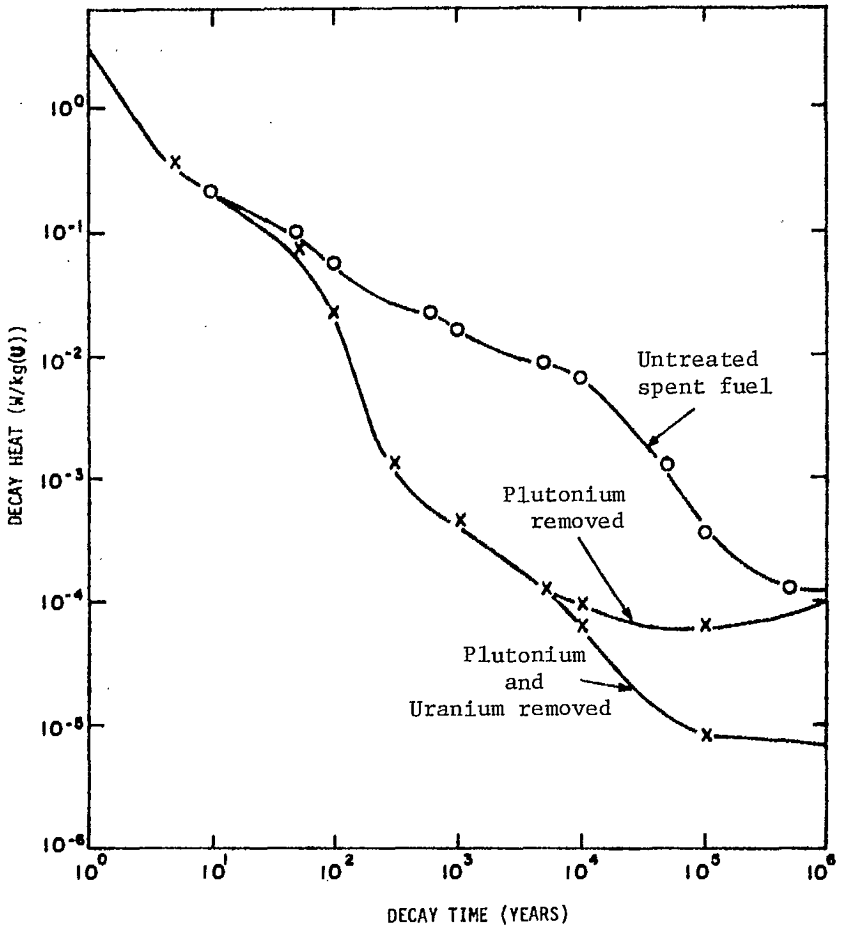

Fig. 3 - Heat produced by various fuel wastes through radioactive decay as a function of time (From "A development program for geological storage of radioactive wastes" by H.Y. Tammemagi; WNRE-259; 19 p; Sept. 1975.)

Fissile material in the irradiated fuel - mainly plutonium in CANDU reactors - could be recovered and reprocessed. It has been estimated that the fissile plutonium contained in the irradiated fuel that will have accumulated by 2005 could have an energy content equivalent to Canada's presently proven conventional oil reserves.

Volume of wastes

Considering only the nuclear wastes that are produced by nuclear generating stations, it can be seen that the untreated spent reactor fuel contains more than 99% of the total radioactivity emitted by the waste products of the entire system. The remaining fraction of a per cent is emitted by materials within the reactor core which have become contaminated by neutron absorption.

The volume of irradiated fuel to be disposed of is very small relative to the amount of electricity produced, or compared with the volume of waste products arising from the use of more conventional fuels under similar circumstances. Only about 1700 tonnes of spent fuel was accumulated by early 1978 in Canada as a result of nuclear power station operations that produced some 10^5 million kWh of electricity. This fuel had a total volume of about 700 m^3. Even assuming that the Canadian nuclear program proceeds as presently planned by the provincial utilities, there would still be an accumulation of only about ten times the volume of irradiated fuel by 1990. This would represent a cube with sides of about 19 m.

Fuel storage

During the initial period of rapid heat and radiation decay the spent fuel is stored at the reactor site in water-filled, double-walled, concrete bays (Fig. 4). This is the period when cooling requirements are most important. The 3.6 m of water on top of the fuel bundles provides adequate shielding. The water in the bay is continuously circulated, monitored and purified. It is believed that subsequent storage in up to 11 centralized water-filled bays will meet all of Canada's foreseeable spent fuel storage requirements up to the turn of the century (Fig. 5). All spent fuel from the Pickering "A" station after 30 years of operation would occupy no more than half a bay.

Experience has shown that storage in water-filled bays is both safe and economical. In Canada, irradiated fuel from reactors has been successfully stored for more than 30 years. Long periods of surface storage also have the advantage of providing cooler waste bundles for eventual underground disposal, and additional time to further consider the merits of reprocessing. Atomic Energy of Canada Ltd. (AECL) is continuing to investigate dry surface storage of spent fuel in concrete canisters (Fig. 6). This method may require less maintenance than by wet storage, and would also generate

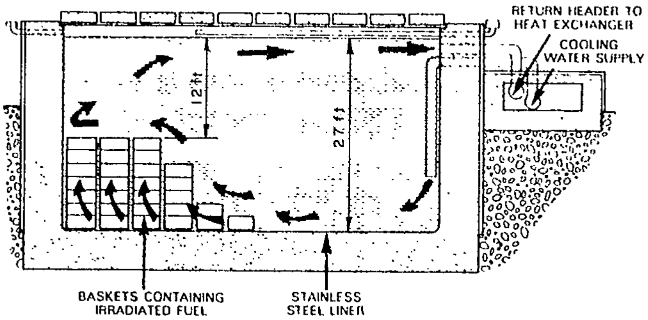

Fig. 4 - Spent fuel storage bay (From "The management of Canada's nuclear wastes" by A.M. Aikin, J.M. Harrison and F.K. Hare; <u>EMR Report</u> EP 77-6; 63 p; Aug. 31, 1977.)

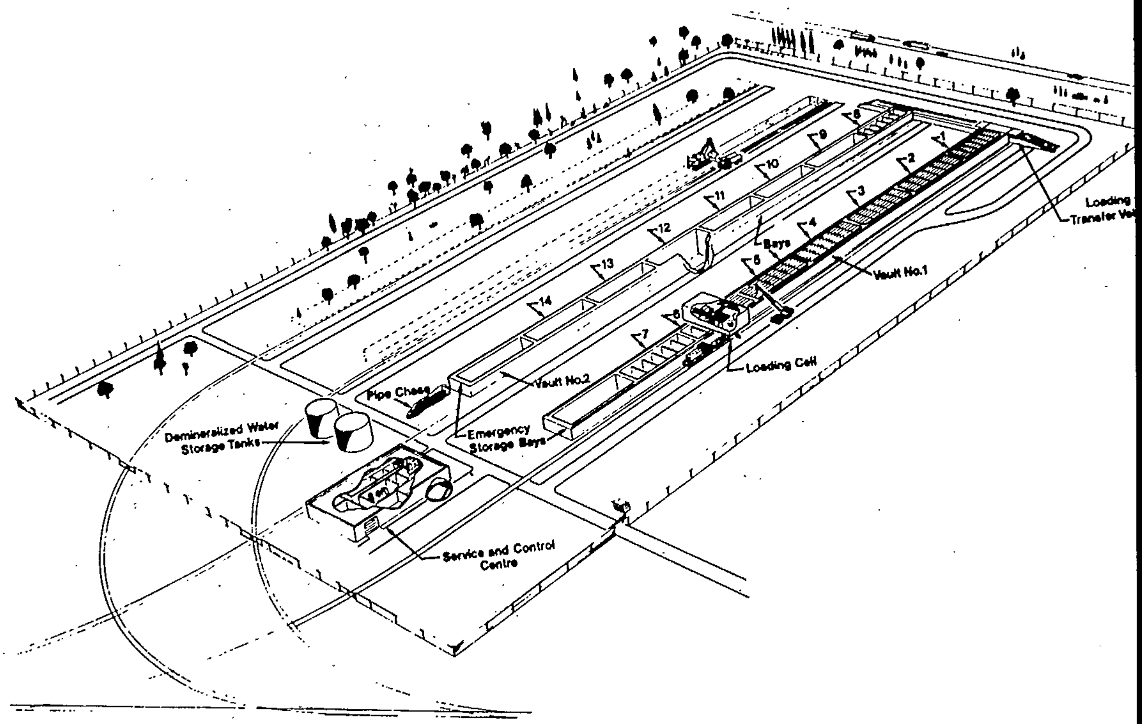

Fig. 5 - Concept of central storage facility for spent fuel (From "Managing nuclear wastes" by P.J. Dyne; AECL-5136; 17 p; May 1975.)

less secondary waste. The intention is to transfer the fuel bundles to these canisters after an initial wet storage period of about five years.

<u>Disposal methods</u>

Although the problem of interim surface storage of the spent fuel bundles has been solved satisfactorily the permanent disposal of high-level radioactive nuclear wastes continues to pose a serious problem. Various methods have been considered including disposal in space, in polar ice caps, under the ocean floor and on land; reprocessing by transmutation of nuclides has also been suggested. The method being given most serious consideration by Canada and other Western countries is deep burial in a suitable geological formation to provide long-term isolation from the biosphere.

To meet the foregoing objectives the government-commissioned Hare report considers the following features as desirable for a potential site:

1. The rock type should be homogeneous and sufficiently large to ensure isolation of the disposal site from any externally imposed changes in environmental conditions.

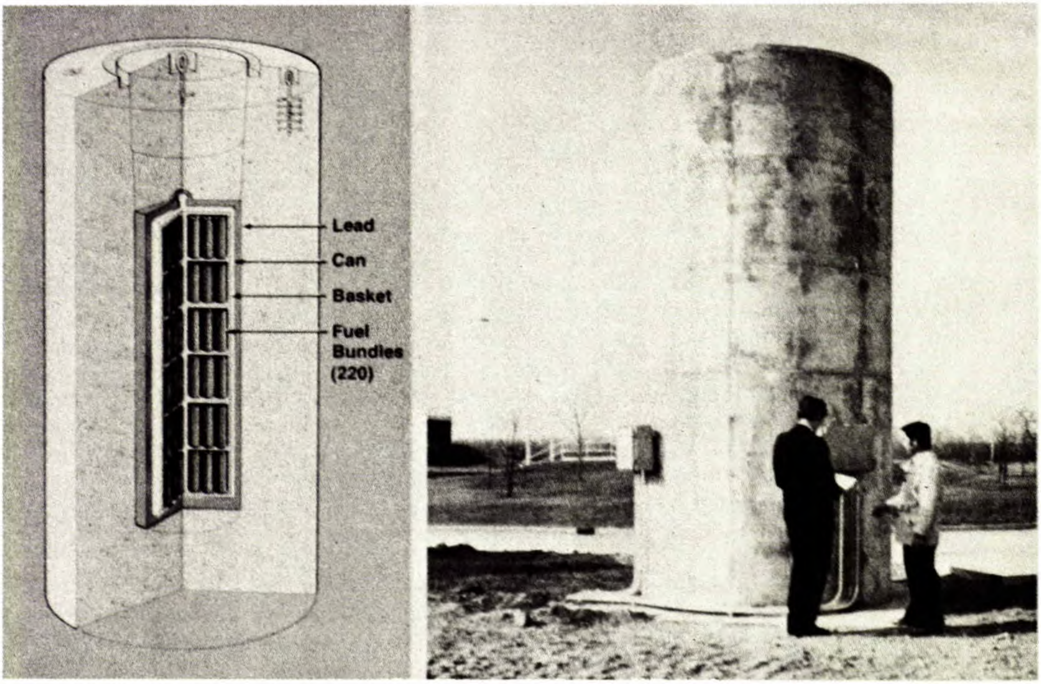

Fig. 6 - Artist's sketch and prototype concrete storage canister for spent fuel (From "Managing nuclear wastes" by P.J. Dyne; AECL-5136; 17 p; May 1975.)

2. Thermal conductivity must be high enough so that heat generated by the wastes will dissipate fast enough to prevent over-heating of the host rock; otherwise the latter could develop cracks or fissures, permitting ingress of circulating water.
3. The host rock should not be affected by irradiation from the contained wastes to an extent that could lead to fracturing, overheating or structural weaknesses.
4. The chemical characteristics of the host formation should be such that a measure of chemical containment is assured in the unlikely event that any waste materials should escape.
5. Groundwater circulation should be low.
6. The site must be in an area sufficiently removed from fault zones so that earthquakes are unlikely to affect the wastes.
7. There should be as little as possible jointing and other characteristics that favour ingress of water.
8. Areas containing nearby mineral or other resources should be avoided.
9. The formation must be sufficiently deep so that the wastes can be buried where they will not be affected by rising or falling sea level, by glacial scouring or deposition, or by major climatic changes such as excessive rain or dryness.
10. Sites should be well removed from all types of human activity that can generate crustal instability, such as deep mining or large dams.

CONCEPTUAL DESIGN STUDY

A conceptual design study of a high-level nuclear waste repository in an igneous rock formation was done for AECL. It provides an indication of the type, size, and relevant costs involved in constructing a repository to handle Canadian nuclear wastes. A distinctive feature of a nuclear repository in addition to mechanical loading is thermal loading.

Thermal loading of host rock

The study was undertaken on the basis that by the year 2025 Canadian waste disposal needs will amount to 700 000 tonnes of spent fuel. This waste would be contained in 1 082 000 canisters 0.36 m in diam and 3 m in length. Initially each canister would emit some 250 W of heat. Canister placement would be such that approximately 32 W/m^2 of heating would be imparted to the surrounding rock mass through the floor of the repository. It should be noted that this heat input would raise the temperature of the rock mass in the vicinity of the canisters to more than 100°C. Today, there is a consensus that the temperature of the rock mass should not be allowed to rise to much more than 100°C, otherwise it can lose strength and develop cracks and fissures. It should also be noted that the natural temperature rise in the earth's crust is in the order of 1°C/30-35 m.

Thermal spalling is another danger that must not be overlooked in certain types of rocks when heating is allowed to rise much above 100°C. Figure 7 graphically illustrates this point in a competent granitic paragneiss at about 315°C. Figure 8 illustrates how the heat wave ripples out with time from the source towards the surface, assuming a radiogenic half-life of 30 years. For example, it shows that the temperature of the host rock 100 m above the repository will rise by 1°C in about 20 years and by 10°C in about 50 years. Isotherms are lines that connect points which have the same temperature at any given time.

Layout of repository

Figure 9 is a conceptual drawing of a single level waste repository consisting of fifty 370-m by 775-m panels linked by ventilation drifts and haulage roads. Each panel contains 50 storage rooms separated by 15-m wide rock pillars. Figure 10 illustrates the planned cross section of the projected repository rooms. The canisters would be placed inside the 0.36-m diam holes drilled into the floor; their tops would be about 1.5 m below floor level. This 1.5-m long space would be backfilled to provide the necessary protection against radiation. The conceptual repository would have a unique dual ventilation system which would permit separation of development and disposal operations. Human access to the disposal rooms is considered desirable for about 50 years, so that the untreated spent fuel may be recovered should a decision be made to reprocess the irradiated fuel for plutonium-239.

Present estimates allow for a disposal facility covering an area of about 3 x 6 km, should the area of the shaft pillar equal the proposed 50-panel disposal area. Shaft pillar is the term normally used to describe the solid block of ore left around the shaft where it crosses the lode, as a protective barrier. The former estimate is based on a heat output of 32 W/m^2. If the allowable heat output is less, then the disposal area will have to be more than the estimated 3 x 6 km. An additional buffer zone or undisturbed

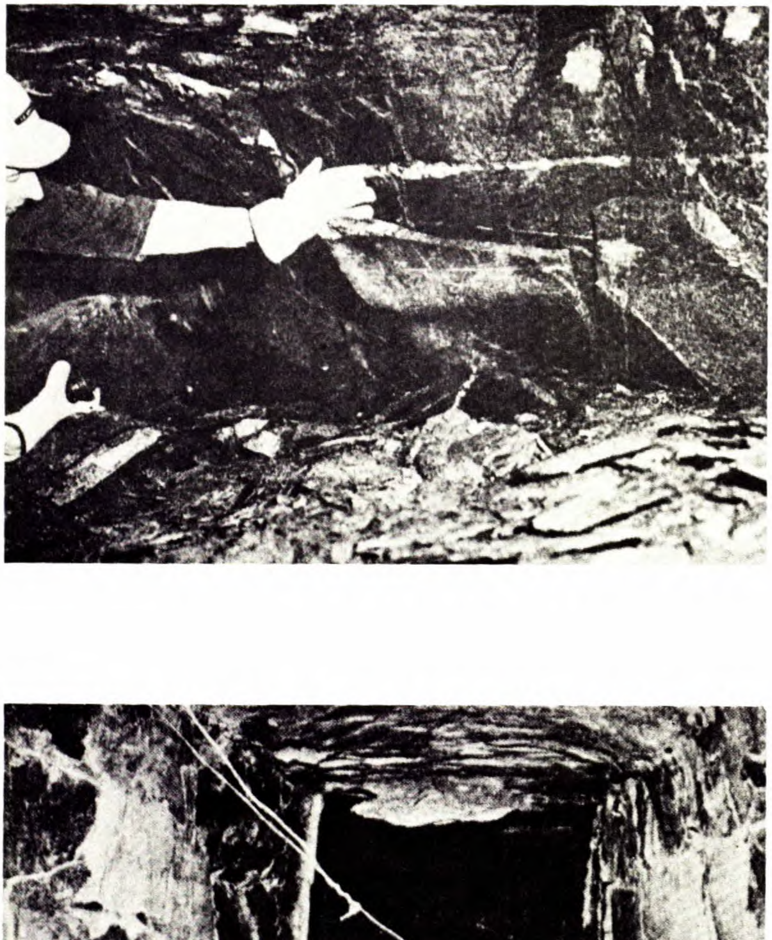

Fig. 7 - Mass of spalls in a test passage (From "Surface spalling by thermal stresses in rocks" by W.M. Gray; Proc 3rd Can Rock Mech Symp; p 85-106; Univ Toronto; Jan. 15-16, 1965, Pub. by Dept. Mines and Tech. Surveys; now EMR Canada; 1965.)

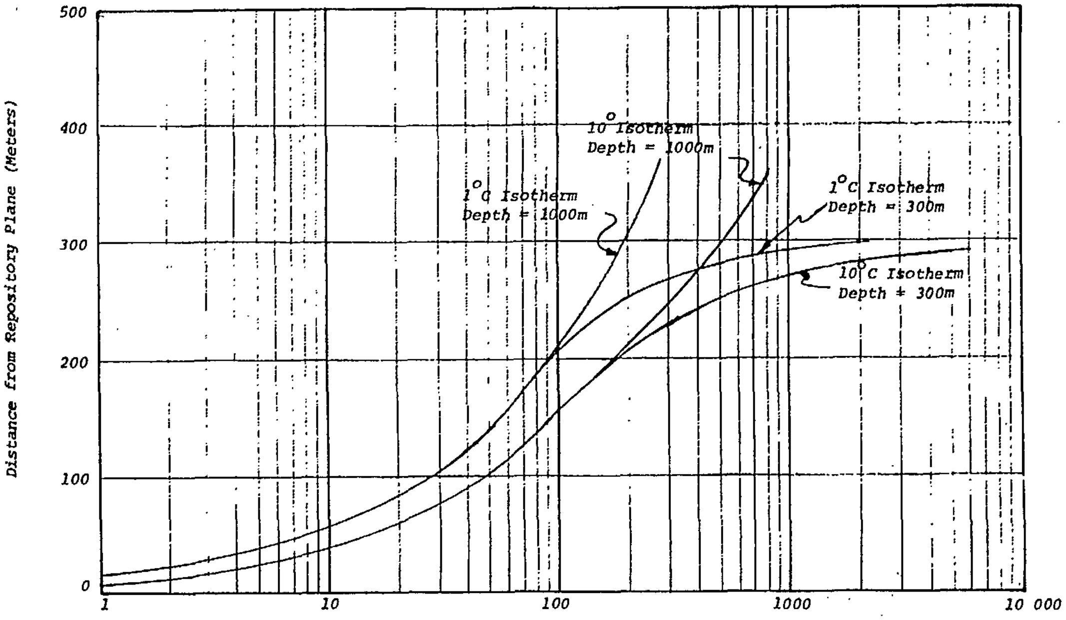

Fig. 8 - Isotherm penetration as a function of time for repositories at 300 and 1000 m (From "Radioactive waste repository study" by Acres Consulting Services Ltd.: Part I, WNRE-359-1; 192 p; March 1977.)

region will also be necessary on surface so that a total land area of about 26 km^2 may be required for waste disposal.

In 1977 the estimated cost of building the conceptual facility described amounted to about $7.5 million. A cost breakdown is shown in Table 3. As may be seen, rock excavation and canister emplacement are the two major cost elements. The overall costs could be reduced if a similar facility were to be located in salt or some other soft rock type, such as shale.

WASTE ISOLATION

Type of barriers

Sufficiently massive barriers must be placed between the burial area of a nuclear-waste repository and the biosphere to ensure non-pollution during the entire period of radioactive decay. Some of these barriers may be man-made, whereas others are geological in nature and, consequently, site specific.

Spent fuel rods constitute the first barrier by being leach resistant, and thus control the release of fission products. By encapsulating the spent fuel a second barrier is interposed. Bitumen and metal alloys, such as lead and zinc, are being considered for this purpose. The waste canister and the cement used around the borehole are the third and fourth barriers. Because these barriers and their chemistry are interactive, the entire system

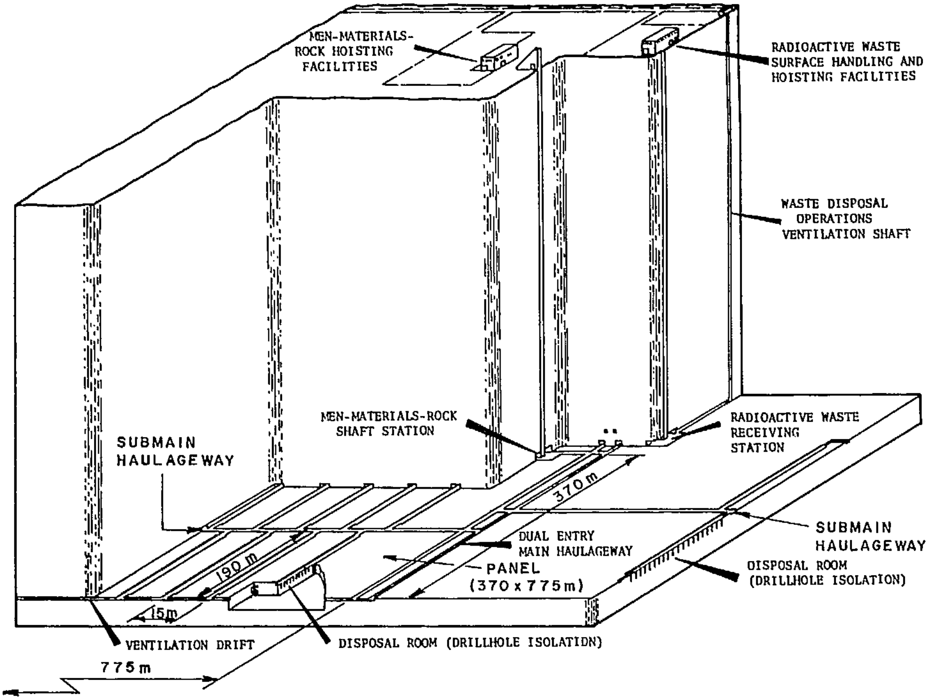

Fig. 9 - Isometric sketch of the single-level reference repository concept (From "Conceptual design of a radioactive waste isolation facility in plutonic rock" by W.H. Grams, P.F. Gnirk, and R.J. Pine; Proc 18 Can Rock Mech Symp; p 4B3-1-11; 1977.)

must be considered when designing a facility. For example, hydraulic cement does not fare well under sulphate ion conditions, and lead is incompatible with chloride ion conditions.

For an underground repository the rock mass represents a fifth barrier. Reliable borehole plugging and shaft sealing methods must, however, be developed and tested to ensure that the mined-out openings do not represent a weak link in the long term. Backfill methods must also be developed that will impede groundwater movement and provide support to the rock walls. Careful consideration is being given to mining methods that will minimize rock damage such as pre-split blasting, which is expensive, and drilling of storage galleries. There is, of course, no point in backfilling to prevent excessive hydraulic migration if induced rock fractures provide alternative pathways.

Phenomena endangering integrity of barriers

A number of naturally occurring phenomena which could break down the barriers between the waste and the biosphere must also be considered when

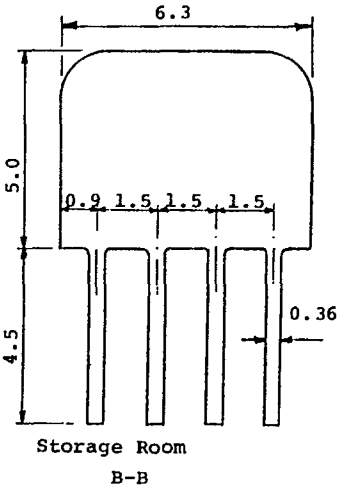

Fig. 10 - Layout of a typical disposal room (From "Conceptual design of a radioactive waste isolation facility in plutonic rock" by W.H. Grams, P.F. Gnirk and R.J. Pine; Proc 18 Can Rock Mech Symp; p 4B3-1-11; 1977.)

selecting suitable locations for nuclear waste disposal. These include tectonism, diapirism, erosion, seismism, and volcanism. In the present case, tectonism, i.e., features resulting from the deformation of the earth's crust, primarily involves faults through the repository. Diapirism involves extrusion, i.e., break in the rock with flow of the salt repository towards the surface. Erosion involves the mechanical wear and transportation of successive layers of overburden. It includes weathering, solution, corrosion and transportation. The mechanical wear and transportation are mostly effected by rain, running water, waves, moving ice and winds. Seismism involves the processes or phenomena brought about by earth movements such as earthquakes. Finally, volcanism involves all phenomena connected with the movement of heated material from the interior of the earth to or toward its surface, e.g., rupture flow of magma through the repository rock.

Should none of the above natural phenomena occur, i.e., should geomechanically static conditions exist, there is still the possibility of a loss of integrity of the geological containment of the long-lived radionuclides due to transportation by groundwater systems. In fact, some of the natural phenomena can modify the groundwater system. However, even if groundwater should ever contact the wastes, the dissolution of radionuclides is effectively retarded because the wastes are immobilized in a highly insoluble form. Moreover, the movement of the radionuclides is further retarded by a number of natural chemical and physical processes such as ion-exchange, filtration and surface adsorption. Disregarding all of these impediments and concentrating only on the hydraulic conductivity of the porous rocks, one can obtain a rough estimate of the time it would take for the radionuclides to re-emerge by considering a natural artesian well type condition. The head gradient in this case may be assumed at 1/50 cm/cm, the ef-

Table 3 - Estimated capital cost of a single-level repository facility. After "Conceptual design of a radioactive waste isolation facility in plutonic rock" by W.H. Grams, P.F. Gnirk and R.J. Pine; Proc 18 Symp on Rock Mech; p 4B3-1 to 4B3-11; 1977.

Item	Cost for 1 082 000 250 W canisters ($ x 10^6)
Shafts: Four, including sinking, lining, hoisting equipment, service lines, etc. (4000 m at $7500 per m)	30
Rock excavation: Includes all haulageways, ventilation drifts, disposal rooms, etc. (15 x 10^6 m^3 at $20 per m)	300
Emplacement: Includes drilling canister emplacement holes plus cuttings removal to surface, transport vehicles, etc. (4.5 m per drillhole x $65.6 per m of drillhole; plus associated costs)	359
Radioactive waste handling facilities Surface: Includes receiving, temporary storage, hot cell, mine hoist loading, control room and decontamination facilities, with shielding and ventilation	20
Underground: Includes special hoist skip, transfer station, temporary storage bays, closed circuit television monitors, control room, emergency and maintenance vehicles, etc. (Excludes overhead crane trucks to disposal rooms.)	6
TOTAL ESTIMATED COST (Excluding ventilation and filtration equipment)	715

fective porosity of granite at 1% and bulk permeability at 10^{-8}cm/s (1.02 x 10^{-5} Darcy)(Fig. 11). The latter figure means that the flow velocity is no more than about 3 km in 0.5 x 10^6 years. The assumed values are not unreasonable considering that the permeability of a laboratory-size granite sample is in the order of 10^{-10} to 10^{-11} Darcy, whereas its porosity is about 0.5%. Using these parameters and Darcy's law, one can estimate it would take about 160 000 years for groundwater to emerge on the surface from

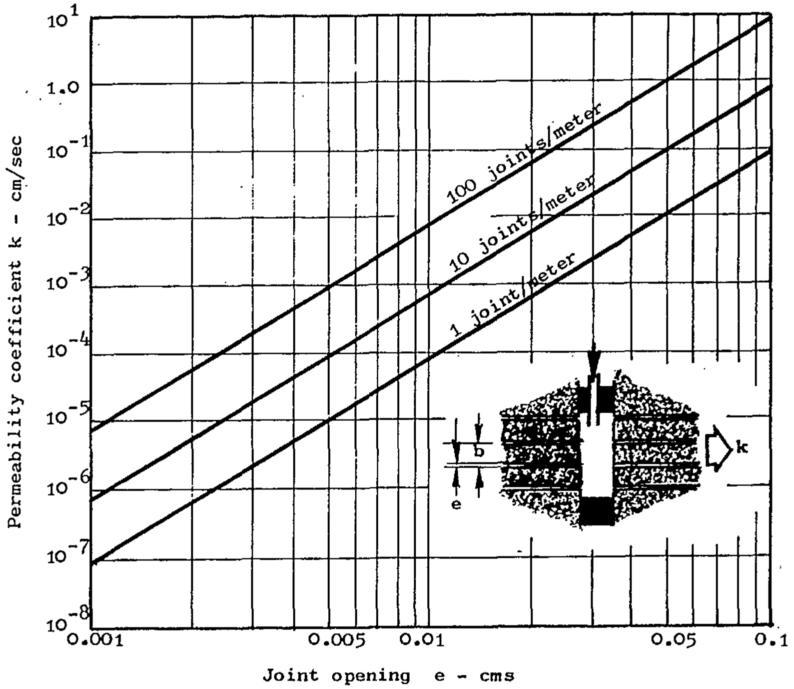

Fig. 11 - Influence of joint opening and joint spacing on the permeability coefficient in the direction of a set of smooth parallel joints in a rock mass (From "Rock slope engineering" by E. Hoek and J.W. Bray; IMM London; 309 p; 1974.)

a repository 1 km deep. During this time the radioactivity of the lightweight fission products will have decreased about 10 millionfold and that of the actinides 5 millionfold. However, complex geology requires a more detailed analysis and investigation.

CANDIDATE GEOLOGICAL FORMATIONS

A variety of geological formations are presently being investigated worldwide for the storage of nuclear wastes in underground mined out structures. The most favourable formations appear to be igneous (plutonic) rock, salt, and shales, each having certain potential advantages. The likely disposal facilities are mined-out structures accessible to humans, at depths not exceeding 1000 m.

In Canada, efforts are currently concentrated on identifying and investigating suitable salt and igneous rock formations (Fig. 12). Relevant identification and investigation studies on igneous rocks will be limited to the Ontario section of the Canadian Shield.

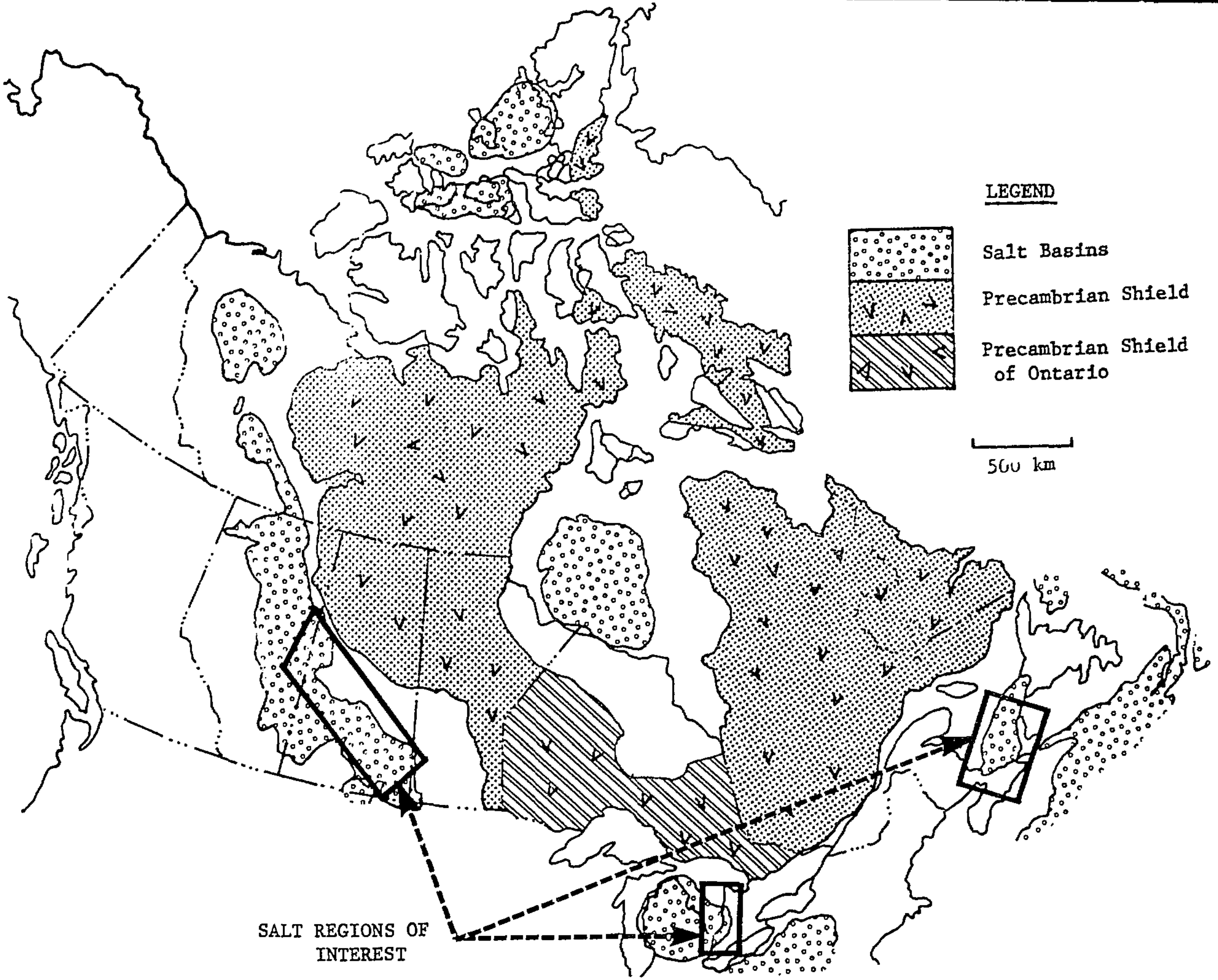

Fig. 12 - The Canadian Shield showing area of immediate interest for radioactive waste disposal by oblique hatching and salt basins of Canada (From "Management of radioactive fuel wastes: The Canadian disposal program" by J. Boulton, (ed); AECL-6314; Oct. 1974.)

The Canadian high-level nuclear-waste disposal program is taking full account of the larger and far more advanced stage of salt-oriented disposal programs that are in progress in the U.S.A. and the Federal Republic of Germany. Advantage is being taken of these foreign programs in evaluating the possibility of locating our waste disposal facilities in Canadian salt basins.

The program involved in the studies to determine the potential of igneous rocks for high level waste disposal requires a much greater Canadian content. These formations have not as yet received the same worldwide attention as salt. Consequently, many more investigative studies and much more research are required to validate the concept of disposal in igneous rock types and to identify potential sites.

Salt

The above factors are of greater or lesser significance depending on the formation in which the waste is to be buried. The presence of salt, for example, is evidence that the area has not been subjected to groundwater activity for a very long time. Lack of isolation and ingress of water would have led to its dissolution. Also any temperature rise due to waste burial will increase its ability to deform, which could improve isolation qualities by causing closure of any openings such as drillholes. Salt also tends to flow under pressure, so that it is self-sealing at depths greater than about 600 m. Earthquakes and other natural cataclysms would, therefore, affect salt much less than other more brittle substances. In addition, salt conducts heat well, so that dangerously high temperature build-ups are most unlikely to develop. However, the presence of any groundwater would lead to the creation of brine solutions which could shorten the life of the barriers. Also salt formations tend to have a low sorptive capacity, thus creating a great dependence on geological integrity to provide an adequate barrier to water transport.

Shales

Shales, as well as granitic rocks, can have a very low permeability. The clay minerals within the shales render them highly sorptive to radionuclide migration. Shales are not as deformable as salt, but more so than igneous rocks. Because of their clay content, however, they are susceptible to phase and chemical changes. Water is driven off some clay minerals at temperatures as low as 100°C.

Igneous rocks

Most igneous rocks, such as granites and basalts, have a very low matrix permeability due to micro-fractures, pores, etc., that exist between the various mineral grains which form the rock. However, the major fracture systems within the in situ rock formations will result in much greater bulk permeability values, as evidenced by comparing the previously quoted laboratory values for granite of 10^{-10} to 10^{-11} Darcy with those of Fig. 11. In situ factors must, therefore, be carefully studied and evaluated to ensure a sufficient barrier to groundwater flow.

Water flow velocities are also affected by in situ stresses in the rock mass, a factor that may be helpful or detrimental when considering waste isolation. The effect could be helpful when it results in tightening the fracture structure and thereby lowers the hydraulic conductivity of the system; it could be detrimental because it adds to the stresses influencing the mined-out repository structures. In the Canadian Shield, horizontal ground stresses are generally larger than the corresponding vertical stresses (Fig. 13). As well, on the Niagara Peninsula in overlying sedimentary formations, compressive backfilling behind concrete linings has been required for power station tunnels to prevent excessive stresses from developing. Figure 14 illustrates the damage caused by high horizontal stresses in the floor of an open pit mine at Marmora, Ontario.

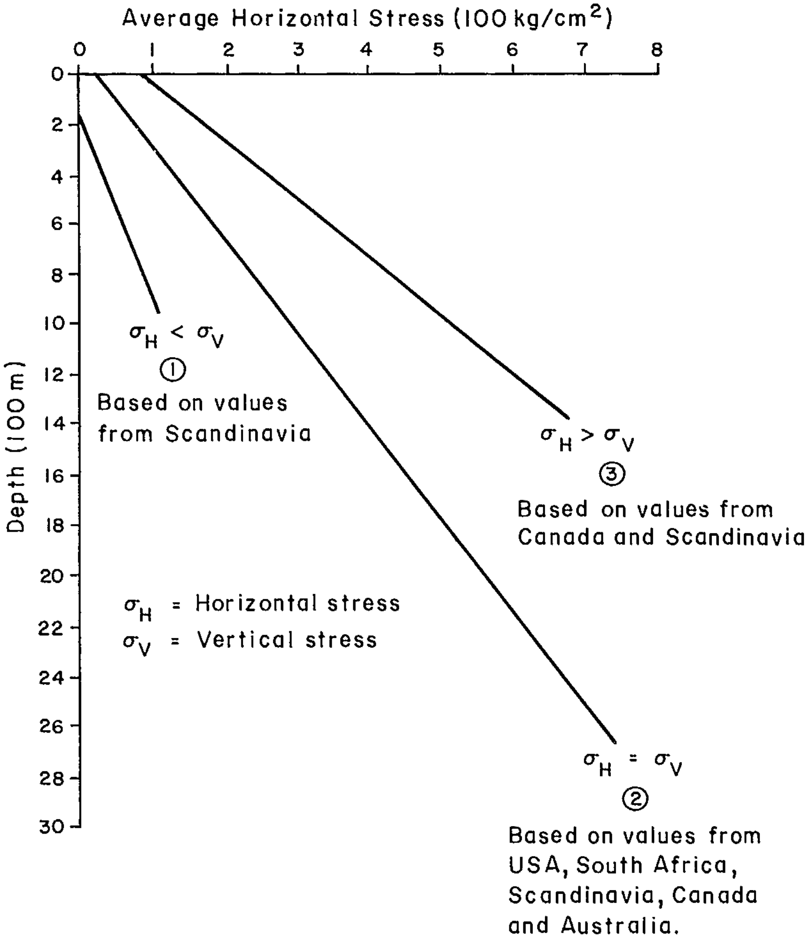

Fig. 13 - Increase of average horizontal stress with depth (From "Ground stresses below 3000 ft" by G. Herget, A. Pahl and P. Oliver; <u>Proc 10 Can Rock Mech Symp</u>; 1:281-307; Queen's University, Kingston, Ont.; 1975.)

Fig. 14 - A 3-m upheaval and floor cracking in an open pit mine indicating the presence of high horizontal stresses (From "Pit slope manual, Ch 5 - Design" by D.F. Coates; CANMET Report 77-5, EMR; 126 p; 1977.)

Apart from the problems due to ground stresses and water flow, the mechanism of radionuclide retardation in igneous rocks will also have to be evaluated.

The detrimental effect of heating the rocks must be carefully considered. Fracturing, or dissolving of minerals and other processes can occur at relatively low temperatures in the order of 100°C as for example, the phenomenon of thermal spalling and loss of water in shales (Fig. 7). All of these mechanisms must be carefully considered to determine the effect on rock strength, deformation and groundwater movement.

SUMMARY

Good prospects exist for solving the technical problems involved in the safe, permanent disposal of high-level reactor wastes and irradiated fuels. The mass and volume of these materials is relatively small; their safe temporary storage in surface facilities does not present a serious problem. The most promising option for Canada appears to be final disposal in deep underground mined-out facilities in igneous rocks. A watching-brief should be maintained on developments in other geological formations such as salt or shales.

Although the overall repository concept appears to be feasible, a number of difficult problems remain to be solved. These include all stages from the initial vitrification and immobilization of the irradiated fuel through transportation, repository design and construction, to final disposal and post-disposal monitoring. Not only technical but environmental, economic and sociological problems must also be dealt with. Present estimates allow for the construction of a demonstration facility by the end of this century and for the construction of a full-scale repository shortly thereafter.

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